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Path-dependency and input substitution: implications for energy policy modelling

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Abstract

In most policy-oriented energy models, the effectiveness of energy policy instruments crucially depends both on the values of the substitution elasticities between the various inputs and on the rates of technological progress. In this paper, we argue that due to the fixed-cost nature of adjustments to relative price changes, these technological parameters are affected by past developments. Failing to account for the role of history will result in biased parameter estimates, and hence the implication for energy policy modelling is that the estimation period should be carefully selected. We provide an empirical illustration using data for the Netherlands.

JEL classifications: O30; Q33; Q48

Keywords: Input substitution; Path-dependency; Energy policy

1. Introduction

Energy economics is a field with a strong modelling tradition, often aimed at analysing the economic consequences of a wide diversity of policy issues ranging from strategic energy-dependency considerations to environmental concerns. In these policy-oriented models the impact of various government instruments on industry input mixes and output levels is to a large extent determined by the substitution

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elasticities between the inputs in production and by the rates of energy-saving technological progress (see e.g. Berndt and Wood, 1975). Therefore, obtaining reliable estimates for the technological parameters of the relevant industries' production functions is essential for the predictive power of these models. Typically, (nested) CES functions are used to describe the production structure of the relevant industries. For an excellent overview of Applied General Equilibrium models we refer to Bhattacharyya (1996). More recent examples are Arikan and Kumbaroglu (2001) and Edwards and Hutton (2001). Whereas the coefficients of most equations in these models are usually derived through calibration, the substitution elasticities and rates of technological progress are in some instances obtained through econometric estimation (Kemfert, 1998).

Here, we argue that the choice of the time period used for the parameter estimation is critical for the validity of energy policy simulation models. Clearly, as for example argued by Bunn and Larsen (1997, p. 3), parameters obtained from time-series estimation are not robust to periods of rapid structural changes. However, we argue that there is a more fundamental problem to ignoring patterns in time-series. Generally, CES regression equations are specified under the implicit assumptions that (i) increases and decreases in relative prices have symmetric, but opposed, consequences for both output levels and the input mix, and (ii) all relative price changes in the same direction have a similar impact independent of past developments (see e.g. Chang, 1994; Kemfert, 1998). However, by now there is a substantial literature on the importance of the role of history in economic behaviour, which invalidates these two implicit assumptions and may have important consequences for policy design.

In Section 2 we discuss these assumptions, some more detail, and their implications are addressed in Section 3. In Section 4 we present the nested CES function that will be used to explore the relevance of taking into account past patterns in time-series data, whereas the regression results are presented in Section 5. Section 6 concludes.

2. Fixed adjustment costs and path-dependency

The assumption of non-zero and constant substitution elasticities between inputs, as implied by CES functions, is not likely to be an appropriate description of firm level production processes; in general, they are better characterised by Leontief technologies (see e.g. Böhringer, 1998). Given its current technology and the associated variable input mix, the firm performs net present value analyses in order to determine the critical (relative) price levels that warrant investment in, for example, either energy-saving or labour-saving technologies.

The fixed-cost (and often, at least to some extent, irreversible) nature of adjustments of the firm's input mix implies that the use of CES functions to describe industry behaviour is warranted only if industry heterogeneity is such that indivisibilities at the firm level are smoothed out at the meso level. However, an additional implication of this adjustment cost view is that relative price *reversals* (e.g. a decrease following an increase in the previous period) are not likely to result in substantial changes in the production structure at the level of individual firms. Some firms may respond to changes in relative prices by investing in a new technology whose input mix is better adjusted to the prevalent relative price structure, but a price reversal is not likely to trigger those firms to immediately undo their investments. Apart from technology depreciation, there is also no incentive to respond to the reversal for firms that did not react to the initial relative price change in the first place; if their NPV analysis did not induce them to adopt a new technology that is better geared to the new relative price structure, the reversal only implies that the discrepancies between the actual and optimal input mix, are reduced.[1]

Controlling for the vintage structure of the capital stock—i.e. taking into account technological and/or economic depreciation—these arguments imply that at the firm level, there is likely to be an *inertia gap* in terms of adjustments to relative price changes. As a consequence, depending on developments in the (recent) past, relative price changes that are similar in terms of both direction and magnitude may have widely different implications for firm behaviour. Hence the implicit assumptions mentioned in Section 1, are generally invalid at the firm level, and they are likely to fail at the industry level as well. If a price increase follows a price decrease, no adjustments are likely to occur; if the previous period also experienced a price increase, the current change may trigger additional changes in the composition of the industry's input mix.[2] Therefore, depending on past changes in the relative price structure, increases and decreases in relative prices are not likely to have a symmetric impact on the industry production structure, and neither do all changes in the same direction have a similar impact. Indeed, these two considerations inspired Hamilton (1996) to argue that only 'all time highs' of the relative energy price are likely to induce new investments in, for example, energy-saving technologies. Earlier empirical studies give evidence of the existence of structural differences with respect to the response to relative price changes both at the micro- and at the macro-level. See for example Hamilton (1988), Kirchgässner and Kübler (1992), Mory (1993), Smyth (1993), Mork et al. (1994), Gardner and Joutz (1996) and Borenstein et al. (1997).[3]

3. Implications

Although we cannot directly test the importance of fixed adjustment costs due to the lack of sufficiently detailed data, we are able to derive important modelling

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[1] Note that taking into account uncertainty about future (relative) prices, sluggishness in investment behaviour at the firm level is exacerbated (see e.g. Bernanke, 1983; Pindyck, 1991). Uncertainty, in combination with irreversibility, implies that firms have an incentive to postpone investments in new (input-saving) technologies as future price reversals may give rise to regret. Therefore, the higher price uncertainty, the higher the critical (relative) price that will trigger investment in input-saving technologies is likely to be. This critical price is typically higher than indicated by simple NPV analyses.

[2] Obviously, entry and exit of firms may show up as changes in the various input-intensities at the industry level. However, controlling for the direction and magnitude of a relative price change, the observed changes will be smaller in case of relative price reversals.

[3] But see Godby et al. (2000) for an analysis that fails to find asymmetries.

implications for empirical studies that employ specific functional forms to describe an industry's production structure (such as CES). Consider the development of energy prices relative to the other input prices in OECD countries over the past 30 years. This time period can roughly be divided into two sub-periods, with a structural break in the mid-1980s. Up to 1986, there is a clear upward trend in the energy price relative to, for example, the wage rate, whereas in the 10 years after 1986 relative energy prices have fluctuated but overall remained relatively stable. On the basis of the literature discussed above, it is clear that simply allowing for a structural break—by using dummy parameters to capture differences in slopes or intercepts—will not do; all parameters in the CES function can be expected to be affected by past changes. More specifically, we can formulate two hypotheses.

In the first place, theory predicts that at the industry level, more substitution will take place in periods where relative price increases result in 'all time highs' (or 'all time lows', depending on the specification of the relative price) than in periods of fluctuating relative prices without a clear trend. Changes in the technology used by individual firms will show up in the industry data as input substitution. Defining the relative input price as the ratio of the energy price to the wage rate, substitution elasticities are expected to be higher in the boom period of this relative price (before 1986) than in its slump (after 1986).

In the second place, if technological progress is predominantly embodied, periods with high rates of investment are likely to experience higher rates of technological progress than periods where investment rates are low. Thus, all else equal, technological progress is also expected to be higher in periods of relative price increases that result in 'all time highs' or 'all time lows' than in periods of fluctuating relative prices without a clear trend. Therefore, we expect rates of technological progress to be lower in the post-1986 period than in the earlier period. This would imply that when aiming to analyse energy policy effectiveness in the second half of the 1990s, the results would be too optimistic when based on technological parameters obtained from using data for the entire post-1973 period. In the following, we will test these two hypotheses using data for the Netherlands by comparing CES regression results using post-1986 data to those obtained on the basis of all observations available.

4. The model

We test the importance of selecting the appropriate estimation period for policy evaluation using data on eight Dutch manufacturing industries over the period 1973–1994. To allow for different substitution elasticities between the various inputs in the production process (capital, energy and labour), nested CES functions will be estimated. The production functions of the various sectors are assumed to have a similar structure, where capital (K) and energy (E) are combined at the first level to produce an 'intermediate output' (which will be referred to as composite input

Z), which is then combined with labour (L) at the second level to produce output (Q); see Eq. (1):[4]

$$Q=\left[B_Z^{-\rho_2}\left[(A_K K)^{-\rho_1}+(A_E E)^{-\rho_1}\right]^{\rho_2/\rho_1}+(B_L L)^{-\rho_2}\right]^{-1/\rho_2} \tag{1}$$

In this equation, ρ_i denotes the substitution parameter at level i ($i=1, 2$); the elasticity of substitution at level i (σ_i) then equals $1/(1+\rho_i)$. The nature of technological change can be derived from the changes over time of the parameters A_K, A_E, B_Z and B_L. Changes over time of B_L, for example, reflect labour-augmenting technological progress. Because of the two-level structure of the production function, there is also a parameter that measures the efficiency with which the composite input Z is used (B_Z). Assuming profit maximisation, solving for the optimal input–output ratio's and subsequently log-differentiating these equations, the rates of technological progress and the elasticities of substitution can be identified using the following expressions:

$$\mathrm{d}q-\mathrm{d}l=\sigma_2(\mathrm{d}w-\mathrm{d}p)+(1-\sigma_2)\mathrm{d}b_l, \tag{2}$$

$$\mathrm{d}e-\mathrm{d}k=\sigma_1(\mathrm{d}r-\mathrm{d}p_e)+(1-\sigma_1)(\mathrm{d}a_k-\mathrm{d}a_e), \tag{3}$$

$$\mathrm{d}l-\mathrm{d}k=\sigma_1(\mathrm{d}r-\mathrm{d}w)+\frac{\sigma_1-\sigma_2}{\sigma_2}(\mathrm{d}z-\mathrm{d}l)+\frac{\sigma_1(1-\sigma_2)}{\sigma_2}(\mathrm{d}b_z-\mathrm{d}b_l)+(1-\sigma_1)\mathrm{d}a_k \tag{4}$$

In the system of Eqs. (2)–(4), q, l, e, k and z are the natural logarithms of, respectively, the amount of output produced, and of the amounts used of labour, energy, capital, and the intermediate input. Similarly, p, w, p_e and r are the natural logarithms of the respective prices, whereas d indicates first differences. Hence, $\mathrm{d}b_l$ reflects labour-augmenting technological progress, and $\mathrm{d}a_k$ and $\mathrm{d}a_e$ are the rates of capital-augmenting and energy-augmenting technological progress.

From an econometric point of view, the system of Eqs. (2)–(4) is underidentified in the sense that generally not all parameters can be uniquely determined; see for example Chang (1994, p. 23). In our case, we can only identify the net *difference* in capital-augmenting and energy-augmenting technological progress (i.e. $\mathrm{d}a_k-\mathrm{d}a_e$); the levels themselves can only be determined under specific circumstances. To see this, note that estimating Eq. (2) yields σ_2, the elasticity of substitution between the intermediate input (obtained by combining capital and energy) on the one hand and labour on the other, as well as the rate of growth of labour-augmenting technological progress $\mathrm{d}b_l$ (as captured by the equation's intercept). Estimation of Eq. (3) yields information on σ_1 (the elasticity of substitution between capital and energy) and, via its intercept, on the *difference* between $\mathrm{d}a_k$ and $\mathrm{d}a_e$. The

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[4] For a discussion of the various ways in which the CES function can be specified, see Kemfert (1998).

Table 1
Summary of the parameters found for the various estimation periods

Coefficient	1974–1994	1974–1986	1986–1994
σ_1	0	0.000634	0
σ_2	0.488788	0.50473	0.45732
db_l	0.025149	0.030439	0.014774
da_k	−0.000529	−0.000895	0
da_e	0.0236	0.041803	0

Zeroes denote coefficients that do not differ significantly from zero at the 5% level.

interpretation of the intercept of Eq. (4) is even more complex: this intercept, which consists of the last two terms in Eq. (4), captures both the *difference* in labour-saving technological progress and technological progress that enhances the intermediate input (i.e. $db_z - db_l$) and the *level* of capital-augmenting technological progress (da_k). This implies that in general, we cannot uniquely identify the growth rates of the capital-augmenting and energy-augmenting technological progress. Only if either $\sigma_1 = 0$ or $\sigma_2 = 1$, the third term in Eq. (4) drops out and the rate of capital-augmenting technological progress is known, and hence, from Eq. (3), the rate of energy-augmenting technological progress as well.

5. Results

We have gathered data on a balanced panel of eight industrial sectors for the Dutch economy. These sectors are agriculture, food and beverages, textiles and clothing, paper industry, basic metal industry, building materials, chemical industry and construction, which were selected on the basis of data availability for a longer time period. Data on energy use and energy prices are not (yet) available for the period before 1973 and after 1994 (at least not measured in a consistent way with the 1973–1994 period), so we restricted the time period to the period 1973–1994.[5]

Applying iterative weighted least squares while assuming common effects, we estimated the model consisting of Eqs. (2)–(4) for three different periods: the entire sample period, and the sub-periods of price increases (1974–1986) and of price decreases (1986–1994). The actual results of the regression are presented in Appendix A; the most important results are summarised in Table 1.[6]

As has been stated above, the nature of technological progress cannot be identified

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[5] We have used three main sources of data. Volumes and prices of value added and labour are taken from the P-series of the National Accounts 1997 of CBS Statistics Netherlands (CBS Statistics Netherlands, 1998). Data on the stock of capital in 1990-prices are provided by the CPB, Netherlands Bureau for Economic Policy Analysis. Data on the use of energy and the price of energy are based on the publication *De Nederlandse Energiehuishouding* (CBS Statistics Netherlands, various issues).

[6] The regression summarised in Table 1 are based on common-effects regressions (i.e. no sector-specific dummies were included). However, we also ran fixed-effects estimation regressions (thus allowing for sector-specific results), which are presented in Appendix B. From these fixed-effects regressions, a similar pattern emerges as is obtained from the common-effects estimations.

unless the substitution elasticities have specific values. However, in all three regressions, the elasticity of substitution between capital and energy (σ_1) is found to be very close to zero or even insignificant, and hence the identification problem disappears: the intercept in Eq. (4) captures exclusively capital-augmenting technological progress, which means that we can calculate the rate of energy-augmenting technological progress from Eq. (3).

The regression results for the entire sample period are presented in the first row of Table 1. Capital and energy are found to be complements whereas the intermediate output and labour are found to be substitutes (albeit imperfectly as the elasticity of substitution $\sigma_2 < 1$). Furthermore, over this period technological change has been fairly substantial for both labour and energy.

Using these regression results in a policy simulation model would lead to the conclusion that energy policies are likely to be effective, and not too costly in terms of growth: input substitution and technological progress are fairly large. However, subdivision of the entire sample period in a period of general price increases (1974–1986) and decreases (1986–1994) contradicts this conclusion: the coefficient estimates differ substantially between the two sub-periods discerned. In the period of increasing energy prices (as presented in the second row in Table 1), the elasticity of substitution between capital and energy is low but significantly different from zero, whereas it becomes insignificant in the period of energy price decreases (as can be seen from the third row of Table 1). Also the elasticity of substitution between the intermediate input and labour, σ_2, is found to have decreased (and significantly so with respect to its value in the first period). Finally, whereas in the period before 1986 technological progress in labour was slightly above 3% and even above 4% with respect to energy use, in the period thereafter labour-augmenting technological progress fell to less than 1.5% whereas energy-augmenting technological progress even fell to zero.[7] This suggests that indeed the two periods differ substantially: an asymmetry exists between periods of high and increasing relative energy prices where technological progress and the elasticity of substitution are fairly substantial, and periods of low and stable energy prices where both technological progress and substitution elasticities are low. This implies that, for example, it is very likely that in the post-1986 period an increase in the price of energy through taxation would not generate a substantial reduction in energy use, and hence that an evaluation of the effectiveness and/or welfare implications of policy instruments is likely to be too optimistic when based on parameters obtained from the entire post-1973 period.

6. Conclusions

In this paper we draw attention to the importance of selecting the appropriate estimation period on the basis of which policy-oriented models can be calibrated. Whereas traditionally time-series data are used to estimated nested CES functions

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[7] Note that as a result of the (close to perfect) complementarity between energy and capital, the observed rate of capital-augmenting technological progress is very close to zero (and even negative in the period 1974–1986).

to describe industry level production functions using as many observations as possible, we argue that the role of history should not be ignored and that, as a consequence, appropriate estimation periods should be selected. Indeed, we state that both the implicit assumptions that (i) increases and decreases in relative prices have symmetric (but opposed) consequences for both output levels and the input mix, and (ii) all relative price changes in the same direction (i.e. increases or decreases) have a similar impact independent of past developments, do not hold. One of the reasons proposed in the theoretical literature is the sunk-cost nature of investments in new technologies required to adjust the firm's production process to relative price changes, which implies that substitution is less smooth than traditionally assumed. Theory predicts that due to the sunk-cost nature of investments, *reversals* of relative price changes will not induce additional investments in new technologies and hence the observed substitution elasticities and rates of technological progress are likely to be lower in periods of fluctuating relative prices without a clear trend, as opposed to relative price changes (similar in terms of both direction and magnitude) in periods of strong upward or downward trends. This suggests that the pattern of past relative price changes will affect these technological parameters and hence that the selection of the estimation period crucially determines the perceived effectiveness of policy instruments.

Due to the lack of firm level data, we cannot test this hypothesis directly. However, from a pragmatic modelling point of view, the main coefficients of interest are the technological parameters of the CES functions that are typically used in policy-oriented energy modelling. Estimating CES functions using panel data for eight Dutch industrial sectors, we conclude that there are marked differences in the substitution elasticities and technological progress parameters between the period of high and increasing energy prices (1974–1986) and the period of relatively low and stable prices (1986–1994): substitution elasticities and the rates of technological progress are significantly lower in the latter period than in the former. These results suggest that energy policy instruments are not likely to be a very effective instrument in periods of fluctuating relative prices without a clear trend, as was the case in the second half of the 1990s. Therefore, our main conclusion is that indeed past developments affect current effectiveness of energy policy, and hence the researchers should be aware of the importance of selecting the appropriate estimation period for their policy analyses.

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Appendix A: Common-effects estimation results

Table A1

Estimation results for the entire sample period (1974–1994) and the two sub-periods; standard errors are presented in parenthesis

Coefficient	1974–1994	1974–1986	1986–1994
σ_1	0.000492	0.000634*	-0.000354
	(0.000314)	(0.000311)	(0.000720)
σ_2	0.488788**	0.504730**	0.457320**
	(0.064726)	(0.080529)	(0.088029)
$\mathrm{d}b_l$	0.025149**	0.030439**	0.014774*
	(0.006198)	(0.008632)	(0.007634)
$\mathrm{d}a_k - \mathrm{d}a_e$	-0.024129^{**}	-0.042698^{**}	0.003891
	(0.006071)	(0.007087)	(0.007522)
$\frac{\sigma_1(1-\sigma_2)}{\sigma_2}(\mathrm{d}b_z - \mathrm{d}b_l) + (1-\sigma_1)\mathrm{d}a_k$	-0.000529^{**}	-0.000895^{**}	4.88E−05
	(0.000112)	(0.000137)	(0.000124)
Standard error of the regression	0.053435	0.027023	0.026196
Sum of squared residuals	0.054251	0.049564	0.061174
Durbin–Watson statistic	1.989492	1.855769	2.094879

[*] Significant at the 5% level.

[**] Significant at the 1% level.

In this appendix, we present the regression results for the system of Eqs. (2)–(4) based on the three estimation periods (1974–1994, 1974–1986 and 1986–1994) (Table A1).

These results are summarised in Table 1, in which insignificant coefficient values (at the 5% level) are denoted by zeroes.

Appendix B: Fixed effects estimation results for the technological progress parameters

Apart from the common-effects estimations that are presented in the main text, we also ran fixed-effect regressions where the technological progress parameters are allowed to differ (the elasticities of substitution are still assumed to be the same

Table B1

Regression results for the substitution elasticities for the three different time periods (using industry fixed effects)

Coefficient	1974–1994	1974–1986	1986–1994
σ_1	0.000478	0.000630*	-0.000360
σ_2	0.447070*	0.478026*	0.402200*

[*] Significantly different from zero at 5% or better.

Table B2
Regression results for the rates of technological progress using industry fixed effects for the period 1974–1994

Industry	db_l	da_k	da_e
Agriculture	0.017227	−0.000105	0.00509
Food and beverages	0.039362*	−0.000624*	0.028606*
Textiles and clothing	0.035026*	−0.000523*	0.038628*
Paper industry	0.037968	−0.000583*	0.034521*
Basic metal industry	0.017785	−0.000978*	0.032746
Building materials	0.015242	−0.003342	0.012503
Chemical industry	0.045138	−0.001603	0.010099

* Significantly different from zero at 5% or better.

across all sectors of industry). Table B1 presents the results with respect to the common elasticities of substitution. These results are very similar to the ones derived from common effects estimation.

The technological progress parameters differ across sectors. For the whole sample period only three or four out of eight sectors produce significant coefficients with respect to energy-saving and capital saving, as can be seen from Table B2.

For the sub-periods we find results (not reported here) which are very similar to the common effects results in Section 5. For the first sub-period the same sectors produce significant coefficients with respect to technological progress. For the second sub-period all technology parameters are insignificant, except one: In the period 1986–1994 we find labour-augmenting technological progress in the food and beverages industry of 4.7%.

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